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FINAL PROJECT REPORT

DEMONSTRATING A VORTEX TECHNOLOGY TO DISINFECT WASTEWATER WITH ULTRAVIOLET LIGHT

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Demonstrating a Vortex Technology to Disinfect Wastewater with UV Light is the final report for the Demonstration of a Vortex Technology for Wastewater Disinfection with UV Light project (contract number 500-09-050) conducted by the University of California - Davis. The information from this project contributes to Energy Research and Development Division's Industrial/ Agriculture/Water End-Use Energy Efficiency Program.

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ABSTRACT

A novel vortex reactor, which uses ultraviolet light for water and wastewater disinfection, was developed. The reactor offers several benefits over commercially available designs, including lower capital and operating costs, improved energy efficiency, easier maintainability and greater efficiency in disinfecting numerous contaminants. These contaminants include a variety of emergent types, including antibiotics, antidepressants, anti-inflammatory drugs, human hormones and personal care products, that are becoming the focus of increased public and regulatory concern. The key difference between this new reactor and conventional reactors is the absence of contact between the water being treated and the lamps that emit the ultraviolet light. Water contact leads to lamp fouling, when a thin film of biological and chemical matter grows on the lamps, reducing the intensity of emitted light. This fouling necessitates frequent cleaning of the tubes, which interrupts the water treatment process. Lamp fouling does not occur in the new reactor. Several reactors were constructed and tested to optimize their design. The tests were carried out at two different wastewater treatment plants for disinfecting total coliforms, and at a national facility for the study of diseases of ornamental plants, where the interest is in neutralizing a quarantine fungus. The results showed that the new reactor meets the regulatory standards for these contaminants. Further tests were performed on emergent contaminants, including a mix of pharmaceuticals and personal care products, which were also successfully broken down by the new reactor. Based on this work, the Regents of the University of California have filed for a patent to protect the intellectual property rights. A grant has also been awarded by the University of California to facilitate the commercialization of this reactor. Discussions are in progress with a major manufacturer of UV systems with a view to licensing the new technology.

Keywords: Water treatment, ultraviolet light, vortex reactor, turbulent mixing, disinfection

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Introduction

The conventional method to disinfect water is by chlorination, a practice with significant drawbacks. When used at reasonable concentration and contact times, chlorination is ineffective for many viruses and protozoa such as *Giardia lampda* and *Cryptosporidium parvum*. When chlorine is used at high concentrations, the interaction with organic material generates numerous harmful byproducts such as trihalomethanes (THMs) and other carcinogens.

In recent years there has been a move away from chlorination in favor of disinfecting by ultraviolet (UV) light. This has happened in nearly all water and wastewater plants in California that have recently been expanded to cope with population growth, or modernized to meet higher standards for discharge. In all of these installations, the UV light applications are performed in commercial reactors using technology nearly a century old. Specifically, these conventional reactors flow water in a channel inserted with banks of UV-emitting tubes. As water flows close to these tubes, the pathogens present are exposed to light at a certain intensity that depends on their proximity to the light source. If pathogens are exposed to UV light at sufficiently high intensity, and for a sufficiently long period of time, then the radiation dose that is delivered (intensity multiplied by exposure) will neutralize or 'inactivate' the pathogens and prevent their growth into harmful colonies. Inherent in these conventional and basic UV system designs are a number of unsatisfactory features that increase the capital and operating costs, and inhibit wider adoption by communities and industries that generate wastewater requiring disinfection. In addition, the UV-emitting lamps come into direct contact with the untreated water and are prone to `fouling'. Fouling is the accumulation of organic and inorganic matter on the outer surface of the UV tubes, which reduces the intensity of the emitted light, decreasing the efficiency of the treatment system. To prevent this from occurring, the lamps are typically placed inside quartz sleeves that are sometimes fitted with mechanical cleaning systems. Alternatively, the lamps are periodically taken out from the contact tank and immersed in an acid solution to remove the film. These systems are costly to manufacture and are expensive to operate. Another unsatisfactory feature of the conventional design is that the channel through which water flows is lined with concrete that can become fouled and must be frequently closed to clean. To maintain continuous operation, several channels are employed, which increases operating costs.

A UV disinfection system that does not require using concrete channels or experience fouling will lower the capital and operating costs and encourage a cleaner, non-chemical method for water treatment.

The New UV Vortex System

A newly developed vortex reactor for water and wastewater disinfection using ultraviolet light eliminates the drawbacks of the conventional UV reactors and offers several benefits over commercially-available designs. These include lower capital and operating costs, improved energy efficiency, easier maintainability and greater efficiency in disinfecting numerous contaminants. Operating this system is fairly straightforward: unhygienic water is introduced at the base of a quartz tube where it rises to form a vortex, confining the water between an air column and the inner wall of the tube. Lamps emitting UV light are placed outside the tube and do not come in contact with the water. Quartz can transmit UV light and when the untreated water is exposed to this light at the required germicidal wave length without lamp contact, `fouling' is eliminated. Since the lamps are located outside the quartz tube they are also easily replaced, reducing down-time from having to lift the heavy UV modules immersed in conventional channels. This new vortex reactor does not require an expensive infrastructure (e.g. heavy-lift cranes, concrete channels) or acid solutions and the capital costs are more affordable. Finally, because the water pressure is reduced inside the vortex, an oxidizing agent such as hydrogen peroxide or ozone can be efficiently introduced into the untreated water to create Advanced Oxidation Process. This process has the best prospects for treating numerous emergent contaminants (e.g. antibiotics, antidepressants, anti-inflammatory drugs, human hormones and Personal Care Products) that are found in wastewater and are of increasing regulatory interest.

Project Purpose

This project conducted experiments to further develop and quantify the effectiveness of the new wastewater disinfection technology using ultraviolet (UV) light in an operational environment, and to demonstrate its benefits, efficiency, maintainability, robustness and reliability to the water quality community. A pilot-scale model of the new UV reactor was constructed, installed at the UC Davis Waste Water Treatment Plant and at other facilities where it was evaluated in an operational setting using actual untreated water. The project also refined the original vortex design based on the test program results and demonstrated its benefits to the water quality community. The project design quantified the disinfection efficiency for a range of flow rates for larger-scale applications.

Project Results

The tests on the new reactor were performed at the UC Davis Waste Water Treatment Plant and the UC Davis Hydraulics Laboratory at Davis, California, the City of Winters Waste Water Treatment Plant and at the National Ornamental Research Site at Dominican University California in San Rafael, California. The tests at the National Ornamental Research Site demonstrated the new reactor's ability to inactivate the pathogens that are common in the horticulture and green-house industries. The horticulture and greenhouse industries are important to California's agricultural economy and are also major users of fresh water, but currenty do not re-use the excess runoff from the growing beds because of the presence of harmful pathogens in this runoff.

At the UC Davis Waste Water Treatment Plant, the tests performed fell into one of two categories. In the first, the reactor was located directly above the conventional UV reactors that are installed at that site. The flow to the new reactor was the same as the flow to the conventional system, and the effluents from both were tested to the same standard allowing treated water to be discharged into a nearby creek. In the second test category, wastewater was extracted from the system at a stage moving through sand filters and the UV system, and was stored in a 500-gallon tank. The water was then dosed with a mixture of emergent contaminants and treated in the new reactor to test its efficiency in breaking down these pollutants.

At the City of Winters facility, the flow to the reactor consisted of wastewater that was treated to only a secondary level and was high in turbidity (cloudy) and suspended solids. Water that is high in these factors does not effectively transmit UV light and usually reduces the efficiency of disinfecting. This did not happen with the new reactor because the vortex insured that the wastewater stream received a UV dose sufficient to reduce the total coliform count to a level that would meet the requirements for water re-use or discharge into a natural water body.

Two sets of tests were conducted at the National Ornamental Research Site. In the first, the wastewater originated directly from the runoff from their ornamental plant beds. In the second, runoff water was stored in a tank and spiked with *Phythophthora Ramorum*, a quarantine pathogen that is a major concern to the commercial greenhouse and horticulture industry.

In all the tests conducted it was demonstrated that the new reactor performs as well as, and in many cases better than the conventional UV reactors that operated at the same sites. At the UC Davis Plant, the new reactor consistently achieved inactivation of total coliforms to meet the standard to be discharged as treated waste water into Putah Creek.

Numerous water-treatment professionals from private consulting firms and state agencies examined the reactor. The vortex UV system was also inspected by commercial greenhouse and horticulture industries operations managers and consultants and operators from the aquaculture industries (fish farms in California are significant users of fresh water but, like the horticulture industry, do not re-use the water due to the presence of contagious pathogens).

The new UV vortex design achieved a higher efficiency in disinfecting a variety of wastewater streams in different applications than the basic model that was available at the start of this project. The project also successfully demonstrated the suitability of the new design in actual water-treatment facilities to industry professionals.

Conclusions

Fresh water is the most valuable and scarce of California's natural resources. This project developed, refined and validated a new vortex technology to disinfect wastewater using UV light. Two major California's industries - horticulture and aquaculture - can reap significant economic benefits including lower capital and operating costs, improved energy efficiency, easier maintainability and greater efficiency in disinfecting numerous wastewater contaminants. This new technology could also expand water re-use for agricultural and recreational purposes in small disadvantaged communities.

The success of this project has prompted the University of California to apply for a patent to protect the Intellectual property Rights of this new reactor, and to facilitate its commercialization. A grant was awarded by the University of California Office of the President to facilitate commercializing this reactor. Discussions are also underway with a major manufacturer of UV systems to license the new reactor and two major utilities are considering funding to install the new system at two disadvantaged communities in California.

CHAPTER 1: Introduction

1.1 Background

Fresh water is the most valuable and scarce of California's natural resources. Water consumption has risen sharply in recent years due to population growth, increased leisure activity, and intensification of commercial activities that use water in abundance. To ensure the availability of this resource in future years, especially under conditions of climate change, much effort is required to conserve water, to distribute it more efficiently, and to re-use the vast quantities of effluent produced from Waste Water Treatment Plants (WWTP), or from the runoff of water-intensive industries such as horticulture and aquaculture which currently are not effectively used. These effluents, if not adequately treated, can pose unreasonable risks to public health. Strict regulations governing their disinfection have been put in place by the Environmental Protection Agency (EPA) as well as by various state agencies. These regulations are designed to protect the public by limiting discharges of harmful waterborne pathogens to natural water bodies, and to ensure that water re-use becomes an asset to society and not a public health risk.

The most common method for water disinfection has been by chlorination. In water re-use applications, chlorine is first introduced into the water to neutralize pathogens, but is then removed from the water before its re-use in agriculture. However, despite its wide-spread use, chlorination is not an ideal solution to water disinfection. For example, chlorine disinfection at reasonable doses and contact times is ineffective against several commonly found viruses and protozoa such as *Giardia lampda* and *Cryptosporidium parvum* (Sobsey, M. D., 1989). Moreover, when applied in large concentrations, chlorine is known to generate chloro-organic, disinfection by-products such as trihalomethanes (THMs) and other carcinogens that persist in the environment (Matsunaga and Qkochi, 1995).

For these and other reasons including the hazards associated with the transporting, storaging and applying highly toxic chlorine, there has been a gradual move in recent years away from chemical disinfection in favor of disinfection using ultraviolet (UV) light. This is evident from the installation of UV systems in newly constructed wastewater treatment plants as well as in those that undergo expansion and modernization. The principle underlying UV for inactivation (neutralizing) of harmful pathogens is that radiation in a specific range of wavelengths (the germicidal range from 200 to 280 nanometers (nm)) leads to DNA mutations within the pathogens and, as a result they cannot reproduce. They become incapable of forming the colonies that cause illness. Apart from UV's non-intrusive character that leaves no residue, UV light has been shown to be effective against both bacteria and viruses. When used in conjunction with an oxidizing agent such as ozone or hydrogen peroxide, UV is effective against a number of emergent contaminants noted above that are the subject of increasing public and regulatory concerns.

1.2 Project Timeline

The work performed under this grant was aimed at further developing and demonstrating a novel technology for water disinfection using UV light based on a prototype of this technology ('vortex reactor') that previously existed. The original prototype, which was first constructed and tested in summer 2008, focused exclusively on the hydrodynamic aspects of the reactor, specifically on devising a method for generating strong rotational motion inside a vertical cylinder. The method had to be robust, easy to construct, inexpensive, and could not involve moving parts. Moreover, the flow inside the cylinder had to be sufficiently turbulent to ensure that adequate mixing was achieved in a relatively short time. Additionally the swirl movment of the wastewater flow had to be sufficiently strong to set-up a central region where the pressure of the rotating fluid was below atmospheric pressure such that it would create an air column at the core of the rotating water. A number of prototypes were constructed and tested and eventually, through a process of gradual refinement, a specific design that met many of the requirements was completed.

Concurrently with the experimental work, (fall 2008) the author collaborated with a team of candidates for the Masters of Business Administration degree at the UC Davis Graduate School of Management to develop a marketing strategy for an innovative technological product. The outcome of the collaboration was a comprehensive business plan to commercialize the vortex reactor. In June 2009, the plan was entered into Big Bang, an annual competition of business plans, where it won the first prize. In fall 2009, a proposal was submitted to the California Energy Commission for a grant to fund to develop and demonstrate the vortex reactor. The final major work performed under this grant was a field trip to the National Ornamental Research Site – Dominican University California (NORS-DUC) where the vortex reactor was installed and tested using runoff water generated from plant-growing activities. The water contained a contagious pathogen that causes considerable damage to the horticulture industry and is the largest obstacle to the re-use of runoff water. Although not originally envisioned in the grant proposal, demonstration of the vortex reactor's potential in recovering this water and making it available for re-use was considered to be an important contribution to the cause of water re-use in California.

1.3 Report Outline

This report describes the further developments that were made to improve the performance of the original vortex reactor, and the extensive validation tests that were performed to assess its performance and efficacy in treating several different wastewater streams in a variety of operational settings. To quantify these parameters, the reactor's performance was evaluated on its ability to achieve the following:

- Treat wastewater to the standards demanded by legislation governing water reuse
- Degrade emergent contaminants that are the subject of increasing regulatory and public concern

- Disinfect non-human pathogens in the runoff from the horticulture industry; an industry that is of vital economic importance to California.

In Chapter 2, the regulatory environment governing the standard of disinfection for each of the requirements is briefly reviewed. Chapter 3 presents a description of the vortex reactor. Chapter 4 details the results obtained at the UC Davis wastewater treatment plant regarding the reactor's performance in inactivating total Coliforms. Chapter 5 presents the results of tests conducted on the reactor at the City of Winters wastewater treatment plant. The reactor's efficacy was tested in inactivating total coliforms in high turbidity waters.

In Chapter 6, results are presented concerning the reactor's performance in inactivating the MS2 bacteriophage, a virus that infects and replicates within bacterium. These tests were carried out at the UC Davis wastewater treatment plant using secondary effluent, which was dosed with MS2 in accordance with the guidelines of the National Water Research Institute. Chapter 7 describes experiments performed at the UCD plant in which an oxidizing agent was used in conjunction with the UV light to study the efficiency of this combination in breaking down a host of pharmaceuticals that were introduced into the plant effluent. This combination constitutes an Advanced Oxidation Process, which is currently the subject of intensive research because of the increasing public and regulatory concern regarding these emergent contaminants. Chapter 8 describes experiments carried out at the National Ornamental Research Site at Dominican University – San Rafael to test the reactor's efficiency in inactivating a pathogen that is specific to ornamental plants. Many of the country's largest plant nurseries and greenhouses are located in California. The ability to disinfect the water runoff from these industries for reuse is economically desirable and is more sustainable than the current management approach. Chapter 9 provides a summary of the main achievements and findings.

CHAPTER 2:
The Regulatory Environment

2.1 Title 22 of the California Code of Regulations: Wastewater Re-Use

Treated wastewater must be disinfected before it is released into the environment or reused in a building to prevent the spread of waterborne pathogens and to decrease public health risk. The initial analysis of the disinfection system for this experiment was to determine if the reactor performed within Title 22 requirements. Title 22 specifies the regulatory standards that must be attained to recycle water for indoor, outdoor and industrial uses in California. To determine if the system met Title 22 requirements, it was tested at two wastewater treatment plants in California using their secondary wastewater in line with their current treatment train and evaluated using the MS2 bacteriophage to determine its operation UV dose.

The University of California at Davis (UCD) Wastewater Treatment plant and the City of Winters Wastewater Treatment Plant were chosen as test sites because they represent two extremes in secondary effluent quality. UCD treats their secondary effluent with UV light, thus their effluent water quality already meets water quality requirements necessary for UV disinfection, namely high transmittance and low turbidity. On the other hand, the City of Winters uses a facultative pond and infiltration to treat and dispose of its wastewater, thus its water quality is not controlled for factors which would diminish the ability for UV light to treat the secondary effluent. The comparison of these two extremes in secondary wastewater quality establishes a qualitative range of performance that can be used to predict performance at other locations.

Similarly, the UV dose must also be determined, because it serves as a quantitative parameter of UV performance. The UV dose serves as a way of standardizing UV reactor performance and is determined using a bioassay, MS2. MS2 is a male-specific (F+) RNA coliphage virus and is used because it has a similar structure to the polio virus and requires a dose of approximately 20 mJ/cm^2 to remove one log of MS2. Thus, the removal of MS2 from the system indicates the removal of polio from the system and indicates the UV dose applied to the system. Depending on the pretreatment of the water and the intended use, NWRI requires UV doses of at least 50, 80 or 100 mJ/cm^2 for water reuse (NWRI, 2012). UV dose can also be used to predict disinfection of multiple types of pathogens in the same waste stream.

2.2 Degradation of Emergent Contaminants

A significant portion of the chemicals found in wastewater are emerging contaminants, newly designed or synthesized chemicals, mostly within the last half-century, that can negatively impact both environmental and human health. These chemicals mainly end up in the environment from treated wastewater discharge, because current wastewater treatment plants were not designed to remove these types of contaminates (Zuloaga et al., 2012). However, treatment with high doses of UV light and an oxidizing agent,(typically hydrogen peroxide) has been shown to help degrade these contaminants (Crittenden, 2003). To determine if the experiment's UV reactor was also able to degrade these contaminants, with and without the assistance of hydrogen peroxide, the UV reactor was again placed in line with the secondary wastewater from UCD where the effluent from the system was analyzed for presence and concentration of these chemicals.

Both detection and measurement of the concentration of these newer contaminants in wastewater streams are difficult.   A typical method known as the a targeted approach seeks to identify and quantify constituents that are known to be found in wastewater streams based on years of previous research. . However, this targeted method can miss newly introduced chemicals, chemicals that are not the focus of research and degradation products (Young & Parry, 2013). To deal with this problem, this study collaborated with Prof. Thomas Young to test his novel high resolution mass spectrometry method that relys on mass accuracy and tandem mass spectrometry to determine likely molecular formulas and structures of the chemicals in the treated wastewater. This method allowed for the total characterization of change in chemical constituents before and after treatment. A separate method paper was written on this technique and presented at the Emerging Environmental Contaminants: Chemistry and Toxicology conference in San Diego, CA (Young & Parry, 2013).

2.3 Addressing Non-Human Pathogens in Recycled Water

Untreated recycled irrigation water has been shown to introduce and spread fungal organisms, such as *Pythium* and *Phytophthora*, in commercial nurseries (Banihashemi, et al., 2010). Water molds are the most active during wet and humid periods and produce flagellated spores called zoospores that can spread through the water. These organisms cause diseases in agriculture, arboriculture and natural ecosystems, and the estimated losses associated with these pathogens are in the billions of dollars (Ghimire et al., 2011).

The spread of *Phytophthora ramorum,* also known as Sudden Oak Death (SOD), is of particular concern in California and is the focus of the validation studies for the reactor. SOD was first noticed in the 1990s, this pathogen causes foliar and shoot blight and bleeding cankers on the tree trunks leading to the death of the plant. This disease is responsible for the death of thousands of trees in California and Oregon and most strongly affects tanoak, coast live oak, California black oak, and Shreve's oak (Rizzo & Garbelotto, 2003).

These tests determined the efficiency in removing *Phytophthora ramorum* in runoff from irrigation water. Preliminary tests were conducted at the National Ornamental Research Site at Dominican University California (NORS-DUC). NORS-DUC is the first research site in the United States dedicated to the study of pests and diseases affecting the health of ornamental plants.

CHAPTER 3:
The Vortex Reactor

3.1 Introduction

The growing popularity of water disinfection by UV light in preference to chlorination is explained by the reliability of this method, by its effectiveness against a wide variety of pathogens and by the absence of the harmful byproducts associated with chemical disinfection. Several commercial UV systems are available; their performance in a wide range of applications is well documented. However, inherent in the basic designs of conventional UV systems are a number of unsatisfactory features that increase the capital and operating costs of these systems and inhibit their wider adoption by the water treatment community. Amongst these features is the fact that the UV-emitting lamps come into direct contact with the untreated water and thus become prone to 'fouling' due to the accumulation of organic and inorganic constituents. To prevent this from occurring, the lamps are typically placed inside quartz sleeves that are fitted with mechanical cleaning systems. These systems are costly to manufacture and are expensive to operate and the ability to do without them would offer significant reduction in costs. Another unsatisfactory feature of the conventional designs is that the reactor is often in the form of a concrete channel through which water flows at a depth of several feet. The costs of construction of the channel, and of the lining needed to prevent bacteria from growing within surface crevices are considerable.

The aim of the work performed under the terms of this grant was to conduct pilot-scale experiments to further develop a novel technology to achieve water and wastewater disinfection by UV light. This technology has the potential for becoming the preferred method for UV disinfection. Briefly, it was found that it was possible to generate a strong water vortex in a long tube while creating a central air core in the form of an elongated cone. By placing the UV lamps on the **outside** of the tube, the untreated water is disinfected without coming into contact with the lamps. This eliminates the problem of 'fouling' and the requirement for quartz sleeves. The electric power required to deliver lethal dose per gallon of water treated will decrease and with it the operating costs of the plant. Also, the lamps become directly accessible from the outside and thus would be easy to replace when inoperative. This will remove the need for expensive infrastructure (e.g. heavy-lift cranes, concrete channel) and will reduce the capital costs involved. The tube itself is made of Teflon which is lightweight, robust, and allows for a high transmission of UV light. Because of the strong swirl induced, mixing in the tube is very intense and this ensures exposure of all untreated water to lethal dose of UV light. Moreover, the centrifugal forces generated by the vortex act to separate the suspended solids from the water column thus facilitating their removal. Finally, because pressure is reduced inside the vortex, powerful oxidizing agents such as hydrogen peroxide or ozone can be efficiently introduced into the untreated water. This will significantly increase the effectiveness of the new UV system and enhance its suitability as an Advanced Oxidation Process.

The specific objectives of the project were to quantify the disinfection efficiency for a range of flow rates, to optimize the technique, and to formulate the appropriate scaling laws. As the acceptance of this technology by the water quality professionals will require a convincing demonstration of its merits in a realistic setting, all the tests will be conducted at the UC Davis Wastewater Treatment Plant where the new system will sit side-by-side with a conventional UV system, using the same untreated water, and its output tested using the same laboratory protocols. This will also facilitate a critical assessment of the maintainability, robustness and reliability of the new technology in an actual operational environment.

3.2 Theoretical Analysis

Understanding the nature of the swirling flow that occurs inside a circular cylinder is desirable from both a theoretical and practical standpoint. This knowledge is also necessary to identify the parameters of the scaling laws appropriate to this reactor. A theoretical analysis based on the fundamental equations that govern fluid motion was therefore carried out. The results are presented in Appendix 1.

3.3 Overall Description

This section briefly describes the most recent design of vortex reactor.. During the project a number of different arrangements were developed and their performance systematically assessed with respect to the twin metrics of disinfection efficiency and hydrodynamic efficiency to optimize the vortex's design. The development process was also guided by the need to make the new reactor inexpensive, and easy to install and operate. To quantify the performance of the vortex reactor, it was important to first understand the hydrodynamic factors that are involved in its operation. Experiments were conducted that were designed to understand the effects of these factors, and to determine the relationships that can aid in the design of larger-scale reactor models that can handle greater flow rates.

The steady-state flow in the vertical reactor is the outcome of a balance of three forces that act on the mass of the water body that is present. These forces are:

- The pressure force that arises when water delivered by the pump at pressure greater than atmospheric rises against the atmospheric pressure that prevails within the cylinder whose top is open to the atmosphere,
- The gravitational force that is associated with the total mass of water present in the vertical cylinder,
- The frictional forces that arise when the moving water comes in contact with both the inner surface of the cylinder, as well as with the air column that forms at the core.

Frictional force has two separate components: one component is aligned with the longitudinal axis of the cylinder. Its effect is to reduce the momentum available to drive the through flow. It plays an important part in determining the total flow rate that can be achieved for a given energy input. The other component of the frictional force act is in the circumferential direction and its effects is therefore to reduce the tangential component of momentum thereby reducing the degree of swirl and with it the extent of mixing that can occur between layers of the rotating water. Energy losses arise from a variety of other sources which include:

- The minor losses that occur in the various fittings used to connect the reactor to the pump.
- Losses that occur when water is pumped into the pressure vessel against the high head that is generated there once steady state conditions are attained.
- Losses that occur when water is forced through the nozzles to generate the swirling motion within the cylinder.
- Losses that are associated with the water flow over the cylinder top which acts as a sharp-crested weir.

The final reactor design incorporated many features that were found to reduce these losses (Figure 3-1). This reactor proved that it is possible to disinfect water flowing at a rate of 50 gallons per minute to the standard required by the discharge permit in effect at the plant.

Figure 3-1: The Vortex Reactor at UC Davis WWTP

Figure 3-2 shows the reactor as rendered using the Auto-CAD drafting software. Untreated water was introduced into the reactor via a 0.75 kW pump. Water is pumped into a pressure vessel located at the base. From the pressure vessel, water flows through a number of nozzles into the quartz cylinder. The nozzles are arranged around the circumference of a base plate. At the center of this plate, there exists a circular hole which is connected to a tube that runs through the pressure vessel and opens to the outside. This hole allows for the low pressure region that is generated at the water's free surface by the action of rotation to extend the entire length of the cylinder thereby creating the air column at the core of the rotating water. The untreated water rotates as it rises above the base plate. The top of the cylinder acts as a weir over which water flows into a collection trough. An outlet is attached to this trough to convey the effluent from this reactor.

A number of UV lamps are arranged in a circle that is concentric with the quartz cylinder. The number of UV tubes was varied. The final design can accommodate 12 tubes, each of which is 34 inches in length and 0.5 inch in diameter. The tubes are attached from their tops to sockets via four prongs. All the electrical connections are located at the top of the cylinder and are thus protected from any leaks that may occur in the system. The cylinders are suspended from the top. Another plate is installed at the free end of these tubes with cavities drilled around its circumference to provide a recess to accommodate the free ends of the UV tubes. This is intended as a safety measure in the event of a tube coming loose from its socket. The sockets are connected to ballasts that are needed to provide the spike in electric voltage required that is required to energize the tubes at the start.

Figure 3-2: Perspective views of vortex reactor

Figure 3-3 shows the reactor with dimensions in inches. The material used for constructing the reactor assembly varied depending on the purpose of the component, and the expected loads upon it. The outer frame was made of welded ¼ inch thick steel channel, the pressure vessel was made of a section of Plexiglas tube kept in place against the internal pressure by a series of stainless steel tension rods. The collection trough was constructed from Plexiglas plates that were glued together in the form of a box.

Figure 3-3: Dimensions of vortex reactor

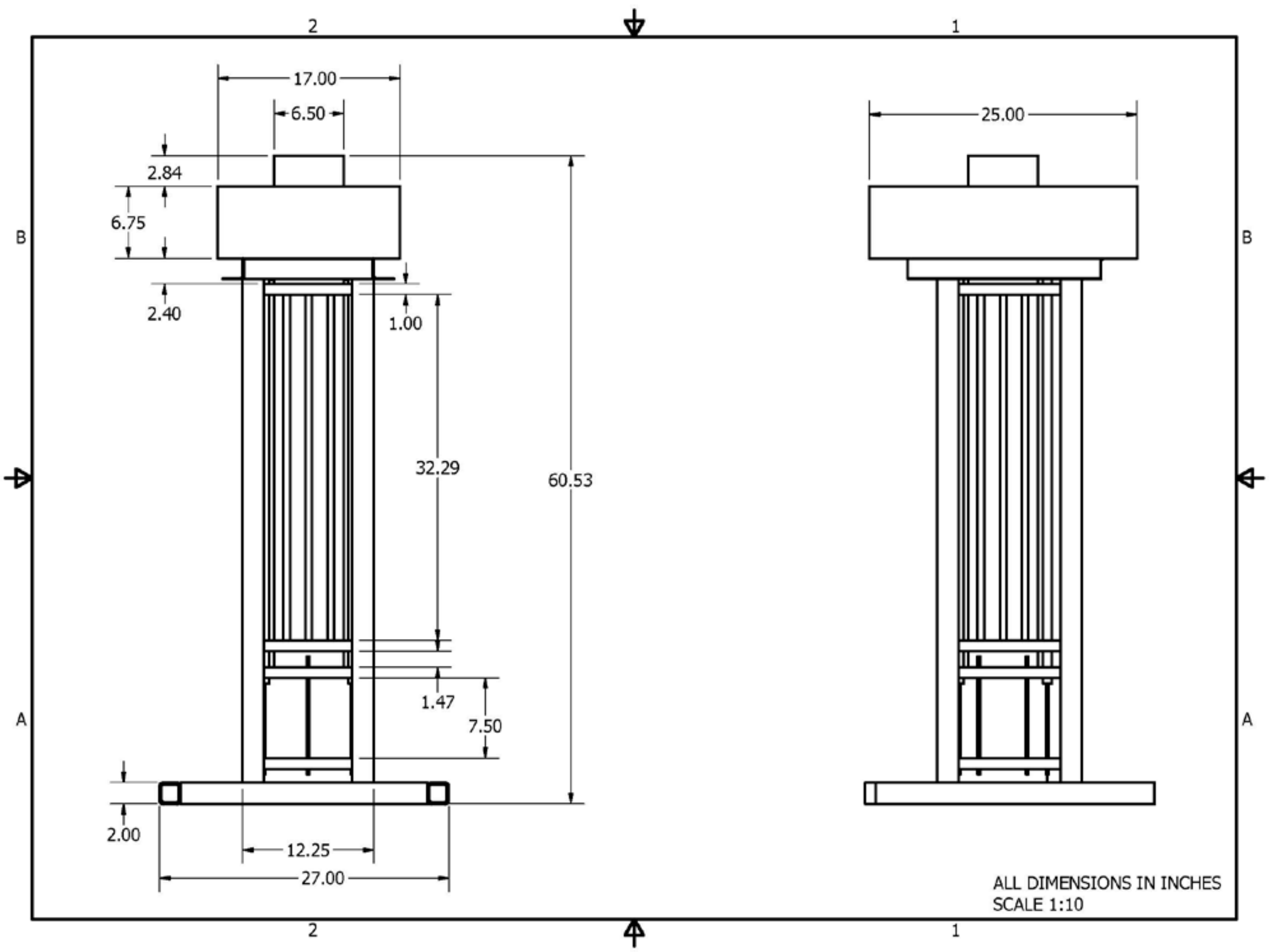


Figure 3-4 shows a cross section through the pressure vessel showing the inner tube whose purpose is to allow the air core to be established and prevent it subsequently from meandering along its length. The cross section also shows the base plate that supported the pressure vessel, and the location of the tension rods used to keep it in place when pressurized.

Figure 3-4: Cross section through the pressure vessel

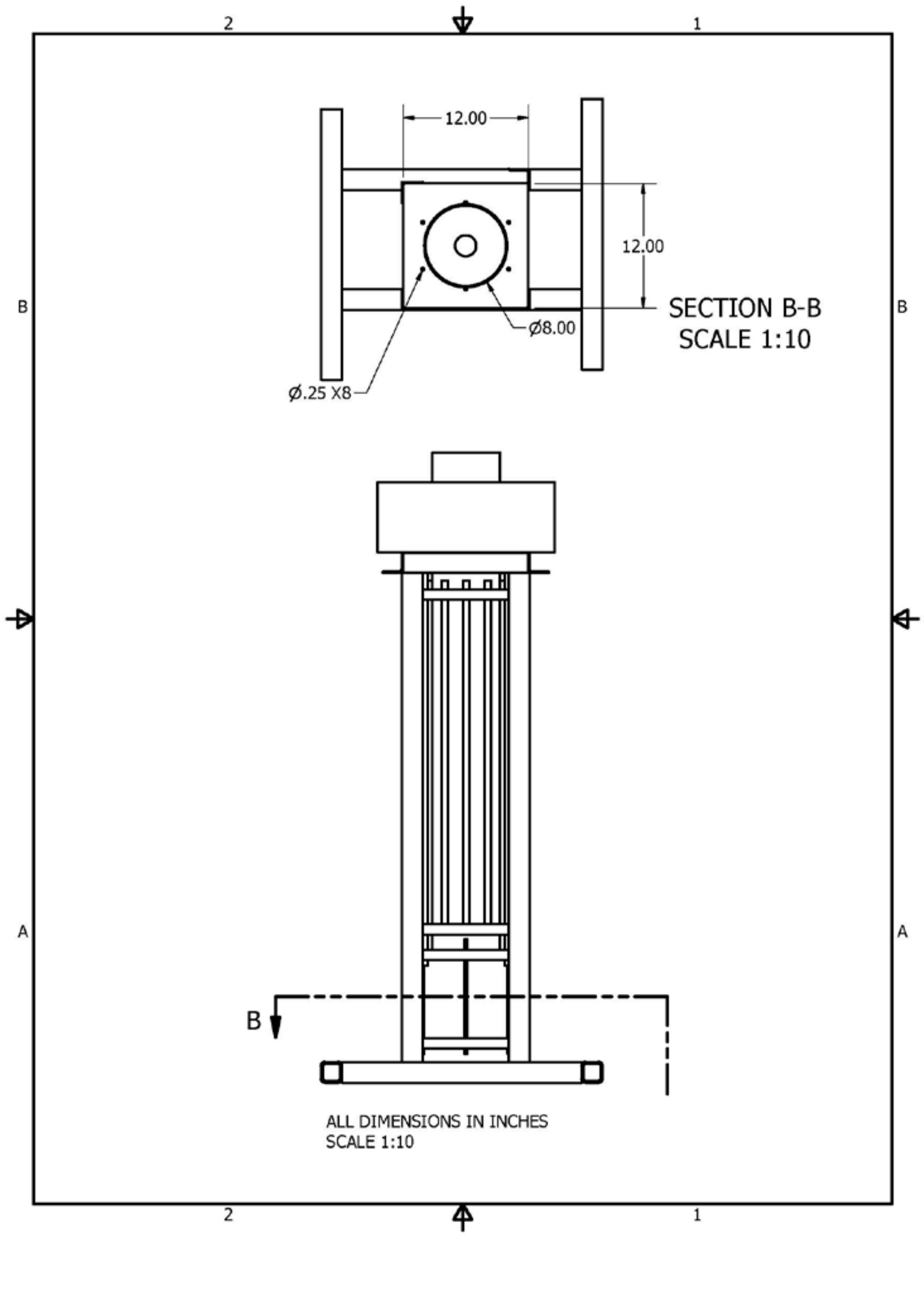


Figure 3-5 shows a cross section through the quartz cylinder and the UV lamps that are arranged in the form of a concentric circle around it. The cross section also shows the locations of the four locator rods, which were made of PVC and whose function was to ensure the alignment of all the separate components that form the reactor.

Figure 3-5: Cross section through the quartz cylinder

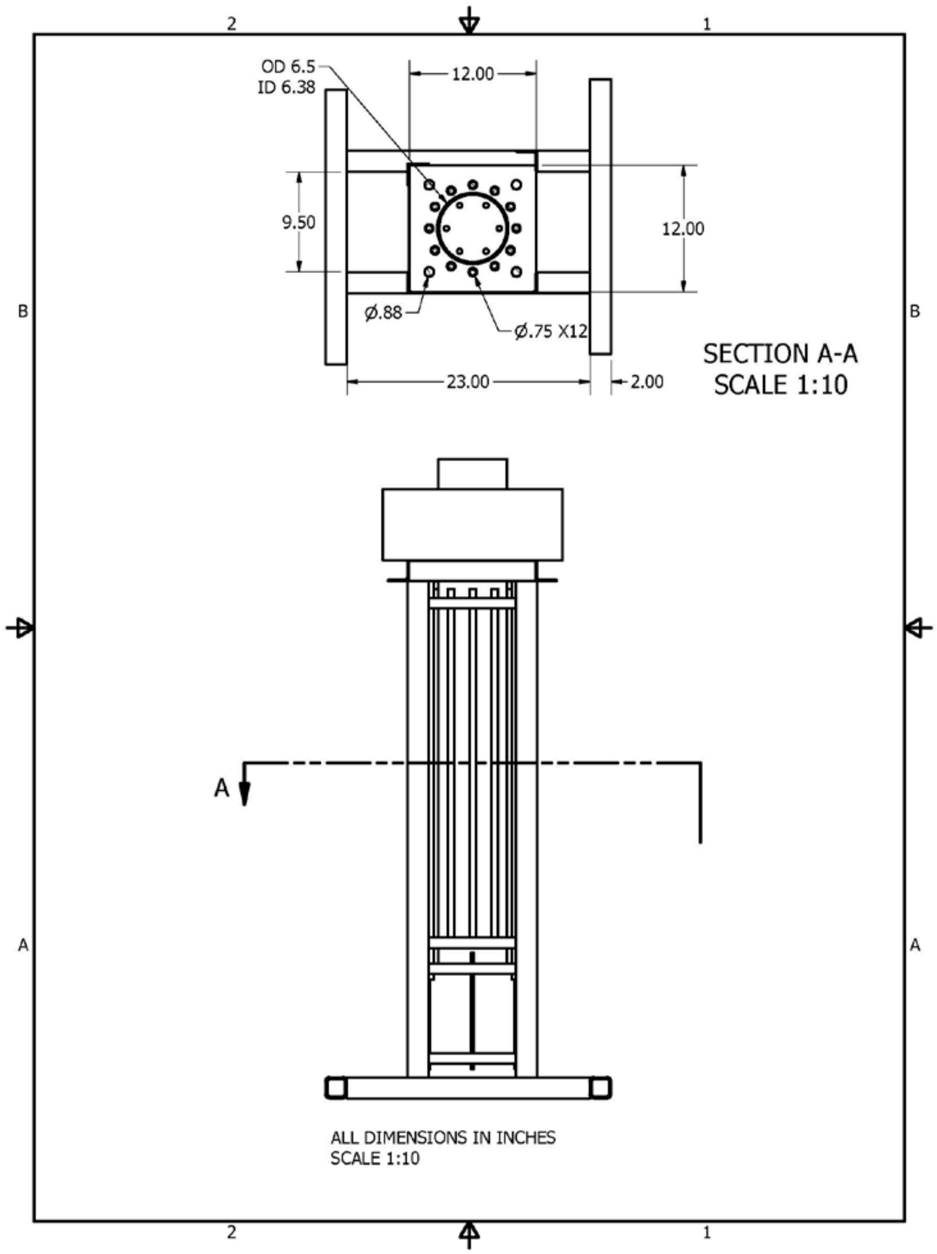
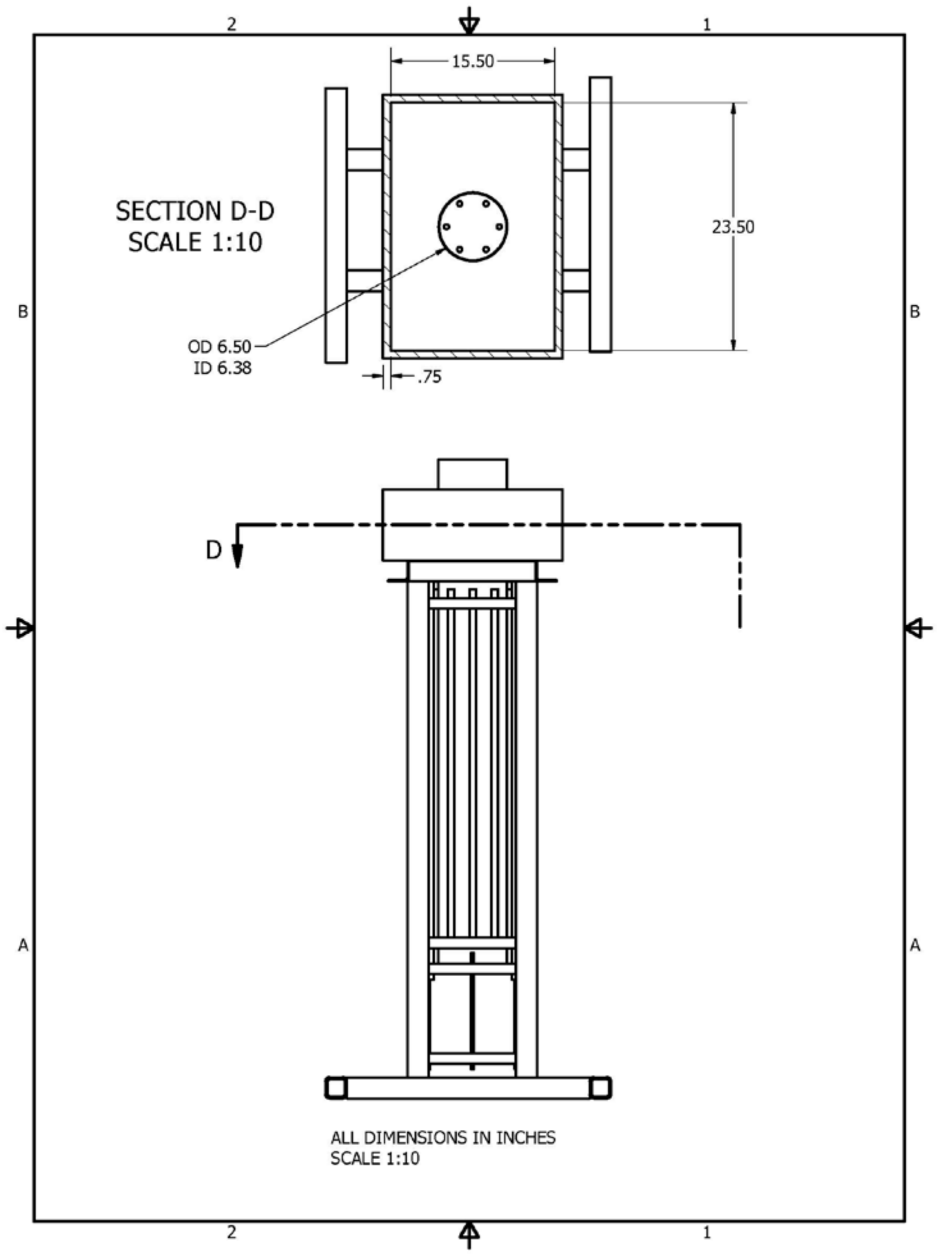


Figure 3-6 shows a cross section through the collection trough. This was made by gluing together five Plexiglas plates. The cylinder protruded through center plate so that it acted as a weir for the effluent to flow over.

Figure 3-6: Cross section through the collection trough



CHAPTER 4: Coliform Analysis at the UC-Davis Wastewater Treatment Plant

For indoor use, such as urinal and toilet flushing, Title 22 requires that the median concentration of total coliform bacteria in a system's effluent not exceed a seven day average of 2.2 MPN(Most Probable Number)/100 mL and that no single sample exceed 240 MPN/100 mL. For outdoors and industrial use, such as irrigation and boiler feed, Title 22 requires that the median concentration of total coliform bacteria in a system's effluent not exceed a seven day average of 23 MPN/100 mL and that no single sample exceed 240 MPN/100 mL. The endogenous coliform bacterial population at a typical wastewater treatment plant using activated sludge and filtration is 1,000 to 100,000 MPN/100 mL (Asano T., 2007). Thus, this experiment's disinfection system must, on average, achieve an average 4-log removal to meet the most stringent water reuse standard. To determine if the system met this requirement, it was tested at two wastewater treatment plants in California using their secondary wastewater in line with their current treatment train. These two sites are the University of California at Davis Wastewater Treatment plant and the City of Winters Wastewater Treatment Plant.

Since the experiment's mode of disinfection is microbial inactivation by ultraviolet light, Title 22 also requires an institute demonstration of a 5-log removal of the virus MS2. Reduction in microbial counts is often measured in "log reduction," the number of organisms removed on a log scale. For example, a 5-log reduction is a 100,000-fold decrease in microorganisms. MS2 is a male-specific (F+) RNA coliphage virus and is used because it has a similar structure to the polio virus and requires a dose of approximately 20 mJ/cm^2 to remove one log of MS2. Thus, the removal of MS2 from the system indicates the removal polio from the system and indicates the UV dose applied to the system (NWRI, 2012). To determine the efficacy of UV light for inactivation MS2, challenge testing was conducted under multiple conditions at the UCD Wastewater Treatment Plant.

The UCD Wastewater Treatment Plant is located about 2.6 miles southwest of the city of Davis, California and 16 miles west of Sacramento, California. The wastewater treatment plant uses activated sludge and rapid sand filtration to treat the wastewater from the UCD campus. The facility discharges to nearby surface water, Putah Creek. The treated wastewater has a low turbidity and high ultraviolet light transmittance (UVT), ideal parameters for UV disinfection to allow the most light through the water column. Turbidity from the sand filters is less than 5 **Nephelometric Turbidity Uni**t (NTU) based on state permitting requirements and transmittance was last tested in October to be at 78.1 percent UVT (California Regional Water Quality Control Board (CRWQCB, 2008).

The UV reactor was placed in line with the secondary effluent from the facilities sand filters and was tested at a constant flow rate of 35 gallons per minute and six different lamp conditions on August 1, 2011. Lamp conditions for the reactor are the number of lamps turned on during the trial. These lamp conditions include: 4, 6, 8, 10 and 12 lamps. One liter of sample was collected from the influent of the disinfection system and one liter for each lamp condition. Samples were analyzed at California Laboratory Services (CLS) in Rancho Cordova, CA for Total and Fecal coliform counts using Colilert Quanti-Tray™ system (IDEXX Laboratories, Westbrook, ME) (Table 4-1). The Colilert Quanti-Tray™ system is a colorimetric method of detecting coliform counts using the Poisson distribution and is approved by the Environmental Protection Agency (EPA) to detect coliforms in drinking and water.

Table 4-1: UCD Wastewater Treatment Plant Total and Fecal Coliform Results (CLS)

	Influent	Lamp Condition					Log Removal
		4 Lamps	6 Lamps	8 Lamps	10 Lamps	12 lamps	
Total Coliform, MPN/100 mL	1600	1.8[a]	1.8	1.8	1.8	1.8	2.9
Fecal Coliform, MPN/100 mL	920	1.8	1.8	1.8	1.8	1.8	2.7
(a) 1.8 MPN/100 mL represents the detection limit for the Colilert Quanti-Tray™ system							

All lamp conditions were able to disinfect the wastewater to the detection limit of the Colilert Quanti-Tray™ system. The results from this experiment show that the UV reactor was able to disinfect UCD secondary effluent to indoor water reuse standards, 2.2 MPN/ 100 mL.

The UV reactor was tested again on August 11, 2011 in the same position with the same flow rate and a lamp condition of 12 bulbs to determine the repeatability of the previous results. One liter of sample was collected from the influent and effluent of the disinfection system. Samples were analyzed at Wuertz lab at UCD for total, fecal coliform and *enterococci* counts using Colilert Quanti-Tray™ system (IDEXX Laboratories, Westbrook, ME) (Table 4-2).

Table 4-2: UCD Wastewater Treatment Plant Coliform Results (Wuertz Lab)

	Influent	12 Lamps	Log Removal
Total Coliform, MPN/100 mL	4839.2	2[a]	3.4
Fecal Coliform, MPN/100 mL	922.2	2	2.7
Enterococcus, MPN/100 mL	186.4	2	2.0
(a) 1.8 MPN/100 mL represents the detection limit for the Colilert Quanti-Tray™ system			

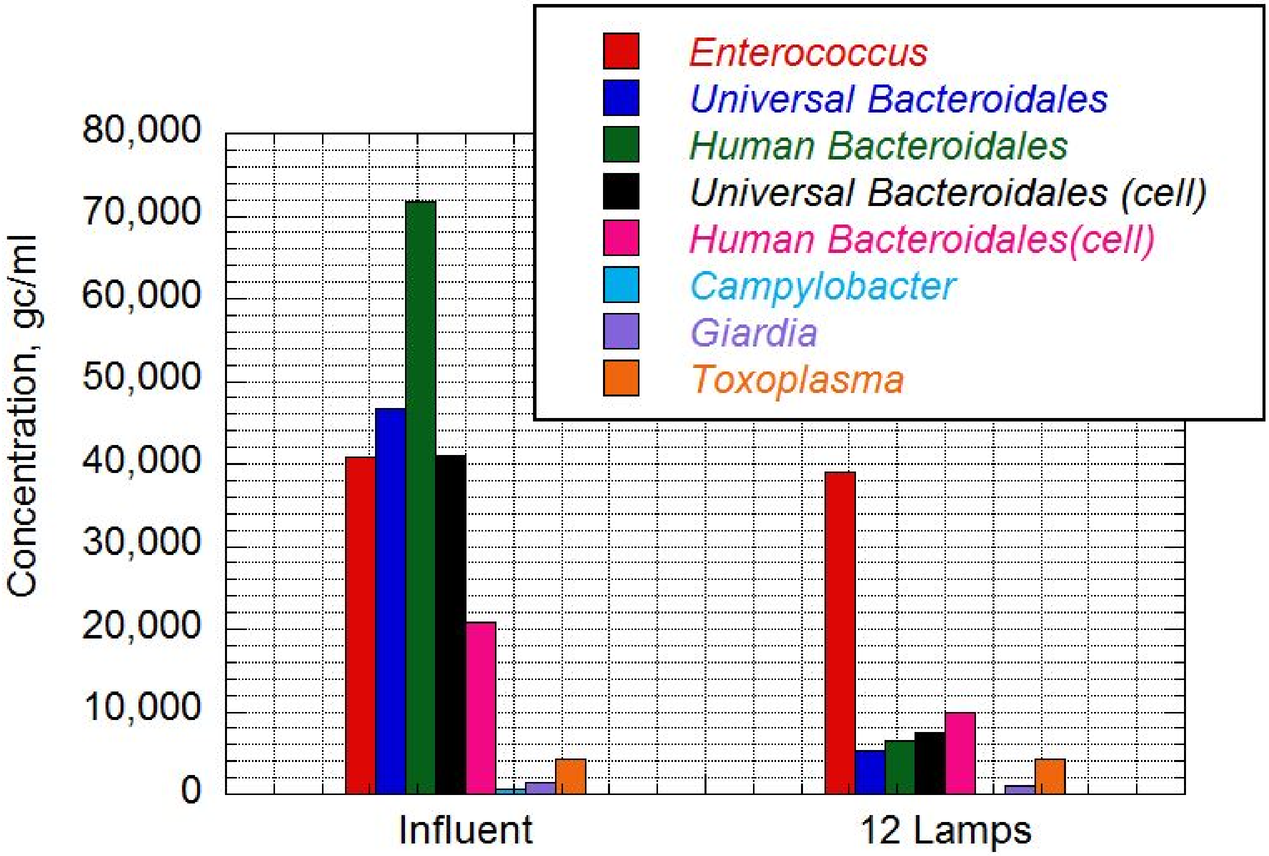
The total coliform counts in the influent for this experiment were three times greater than the previous experiment on August 1, 2011, because water use is not constant with time. Despite this increase in coliform counts, the UV reactor was able to disinfect the wastewater to the detection limit of the Colilert Quanti-Tray™ system and function within Title 22 indoor water reuse standards, 2.2 MPN/ 100 mL.

The analysis of the removal of total coliform and fecal coliform is a standard way to predict the potential pathogenic risk of the treated wastewater. However, it only looks at a subset of culturable bacteria and completely ignores the risk of other pathogens, such as viruses. Thus, the Wuertz lab utilized a better way to assess pathogenic risk in the water sample by measuring the microbial load directly using real-time polymerase chain reaction (qPCR). The qPCR is a laboratory technique that quantifies the amount of microbial species based on the number of copies of genomic DNA per milliliter of sample (gc/mL). Table 4-3 and Figure 4-1 list several species of harmful bacteria and viruses derived from humans, cows, dogs and cats found in the secondary effluent and the 12 lamp treated wastewater. Treatment of the secondary wastewater with the 12 lamps in the reactor shows a significant decrease in all species originally present, except *enterococcus*.

Table 4-3: UCD Wastewater Treatment Microbial Populations by Species (Wuertz Lab)

	Influent 1, (gc/ml)	**12 lamps, (gc/ml)**	SLOD[a], (gc/ml)
Enterococcus	4.08E+04	3.89E+04	402
Universal Bacteroidales	4.66E+04	5.29E+03	140
Human Bacteroidales	7.18E+04	6.50E+03	294
Cow Bacteroidales	ND	ND	18
Dog Bacteroidales	ND	ND	372
Universal *Bacteroidales* (cell)	4.10E+04	7.42E+03	402
Human Bacteroidales (cell)	2.08E+04	9.98E+03	140
Cow Bacteroidales (cell)	ND	ND	18
Dog Bacteroidales (cell)	ND	ND	372
Campylobacter	6.76E+02	ND	36
Salmonella	n.d.	ND	12
Cryptosporidium	n.d.	ND	24
Giardia	1.33E+03	9.42E+02	60
Toxoplasma	4.15E+03	4.26E+03	120
Vibrio cholera	ND	ND	18
Adenovirus C	ND	ND	36
Adenovirus 40/41	ND	ND	102
Norovirus GI	ND	ND	12
Norovirus GII	ND	ND	18
Rotavirus	ND	ND	216
Enterovirus	9.42E+02	Not analyzed	12
[a] SLOD is the "sample limit of detection"			
[b] ND indicates "non-detection"			

Figure 4-1: Reduction in Microbial Populations



CHAPTER 5:
Coliform Analysis at the City of Winters WWTP

The City of Winters Wastewater Treatment Plant is located about 4.1 miles northwest of the City of Winters and 23 miles west of Sacramento, CA. The wastewater treatment plant utilizes aerated facultative lagoons and discharges the treated wastewater via land application. Because the wastewater is treated in lagoons, high algal populations occur during the summer. Therefore, the turbidity of the water was high when it was assessed in July 2013. It was 75 NTU. High turbidity is not ideal for traditional UV-disinfection systems, because particulates in the water can shield pathogens in the water from the UV light.

The UV reactor was placed in line with the effluent from the facultative lagoons and was tested at a constant flow rate of 35 gallons per minute and three lamp conditions on July 9, 2013. These lamp conditions included: 4, 8 and 12 lamps (Table 5-1). One liter of sample was collected from the influent of the disinfection system and one liter for each lamp condition. Samples were analyzed at ExcelChem in Rocklin, California for total coliform counts using Colilert Quanti-Tray™ system (IDEXX Laboratories, Westbrook, ME).

Table 5-1: City of Winters Wastewater Treatment Plant Total Coliform Results (ExcelChem)

Sample Name	Influent	4 Lamps	8 Lamps	12 Lamps	Average Log Removal
Total Coliform, MPN/100 mL	1600	7	7	4	2.4

Results of 7 and 4 MPN/100 mL were not considered significantly different, thus effluent microbial concentrations were combined to determine an average log removal of 2.4 for the system. The results do not meet the Title 22 requirements for indoor water reuse, 2.2 MPN/100 mL, but are well within the requirements for outdoors reuse, 23 MPN/100 mL.

Water quality parameters, such as alkalinity and metal content, were also assessed to identify factors which may impact the effectiveness of UV disinfection for this wastewater stream. A subset of analyzed parameters are included in Table 5-2, alongside the concentrations found in the city of Winters drinking water system and the typical increase in mineral content due to domestic water use.

As seen in Table 5-2, the domestic use of water in the City of Winters waters causes a greater than typical increase in mineral content for total alkalinity, total dissolved solids, chloride, sulfate and sodium. Thus, acid washing of the quartz crystal sleeve would have to occur more regularly to remove mineral deposits at this site if it were to employ UV disinfection. The iron content is also of a concern for the use of UV disinfection, because iron will adsorb UV light and decrease its germicidal ability (Asano et al., 2003). In general, the recommended limits for iron and hardness are no greater than 0.1 mg/L and 140 mg/L, respectively (DeMers & Renner, 1992). As shown in Table 5-2, the City of Winter's Lagoon effluent falls within recommendations for iron, but far exceeds recommendations for hardness. To evaluate the true impact of hardness on this UV reactor design, a long-term study will be needed.

Table 5-2: City of Winters Water Quality Analysis Results

	Winters Lagoon Effluent	Winters Drinking Water[a]	Change in Mineral Content	Typical Mineral Increase in Municipal Wastewater[b]
Wet Chemistry				
Total Alkalinity, as mg/L CaCO3	394	260	134	60-120
Total Dissolved Solids, ppm	769	380	389	150-380
Total Hardness, ppm	380	290	90	
Ion Chromatography				
Chloride, mg/L	157	21.5	135.5	20-50
Sulfate as SO4, mg/L	73.7	35.5	38.2	15-30
Total Metals				
Calcium, µg/L	58200	46500	11700	6000-16000
Copper, µg/L	9.1	250	-240.9	
Iron, µg/L	46	ND		
Lead, µg/L	ND	ND		
Sodium, µg/L	134000	23000	111000	40000-70000

[a] Based on City of Winters 2012 Water Quality Report

[b] Adapted from Asano et al. (2003)

[c] ND indicates "Non-detection"

CHAPTER 6:
MS2 Testing at the UCD WWTP

The reactor's ability to remove MS2 - an icosahedral, positive-sense single-stranded RNA virus that infects the bacterium *Escherichia coli* and other members of the *Enterobacteriaceae* - was assessed at the University of California - Davis Wastewater Treatment Plant on August 30, 2013. Samples were collected in Davis, California and arrived at Biovir Laboratories, Inc. in Benicia, California on the same day according to the National Water Research Institute (NWRI) sampling guidelines (NWRI, 2012). Biovir Laboratories, Inc. both propagated the stock of MS2 (ATCC 15597-B1) and enumerated the MS2 in each of the samples from this experiment according to standard methods (APHA, 2005).

Five lamp conditions were tested for two trials with different water types: water with 70 percent UVT and water with 95 percent UVT. These lamp conditions include: 4, 6, 8, 10 and 12 lamps. The UVT was adjusted using instant coffee, an approved NWRI method (NWRI, 2012). Each trial of the experiment used one liter of MS2 with a titer of 10^{11} polyurethane foam unit per milliliter (PFU/ml) for a final influent concentration of 10^8 PFU/ml. One liter of sample was collected for collimated beam testing. This sample was used to generate a dose response curve to determine the operational UV dose. During the experiment, and for each lamp condition, a 100 ml of sample was collected to measure inactivation. One flow rate was tested, 35 gallons per minute, assuming a fixed design flow rate with alternating lamp conditions.

Title 22 requires a demonstration of 5-log removal of MS2 and the use at least two reactors in series for redundancy to ensure a minimum level of safety in the system (NWRI, 2012). Since only one reactor was tested, it must achieve at least 2.5 log removal of MS2 or a UV dose of 50 mJ/cm^2. A dose of 50 mJ/cm^2 is an approximate UV dose for 2.5 log removal. Figure 6-1 and Figure 6-2 show the average log inactivation of MS2 and the average UV dose in the reactor with respect to change in bulb condition. From these figures, the reactor must operate with at least six bulbs at a UVT of 95 percent and at least eight bulbs at a UVT of 70 percent to achieve a minimum of 2.5 log removal of MS2. If only the 50 mJ/cm^2 UV dose condition is considered then, the UV reactor must operate with at least 4 bulbs at a UVT of 95 percent and at least six bulbs at a UVT of 70 percent.

Figure 6-3 is graph of the energy used by the reactor to achieve a log of MS 2 inactivation for every 1000 gallons. Based on the Figure, more energy is needed to removal a log of MS2 at a UVT of 70 percent than 95 percent. Also, energy use per log removal at 95 percent UVT for 6, 8, and 12 lamps appears to flatten out around 6 lamps, while energy use at a UVT of 70 percent continues to increase for every lamp condition.

Figure 6-1: Average Log Inactivation of MS2

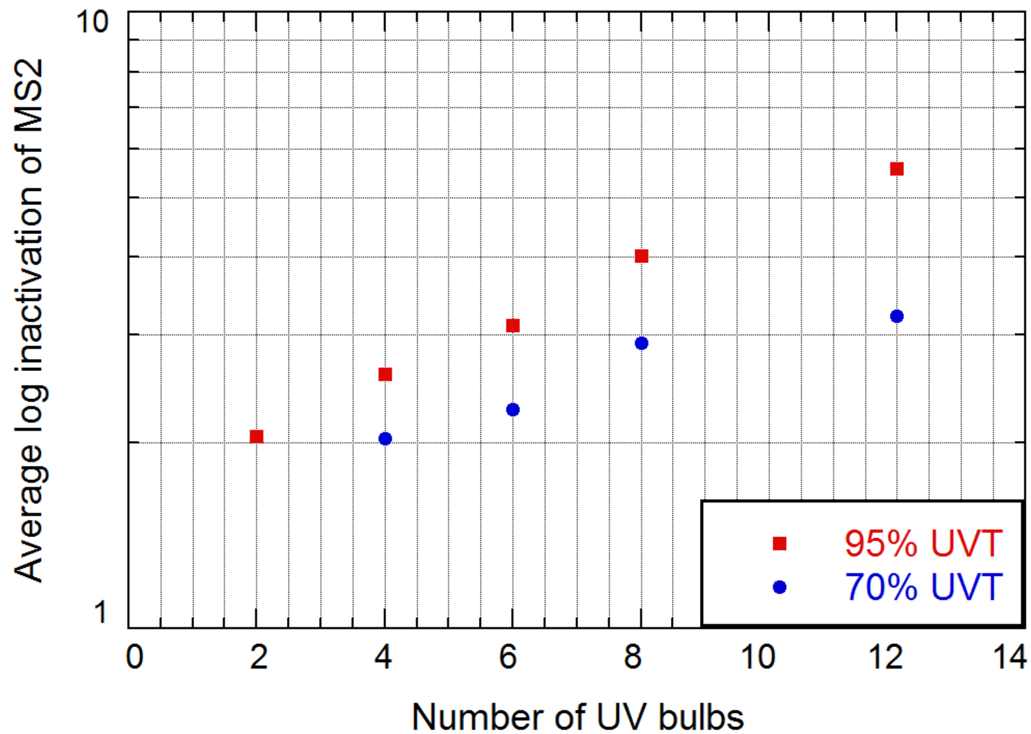


Figure 6-2: Average UV Dose

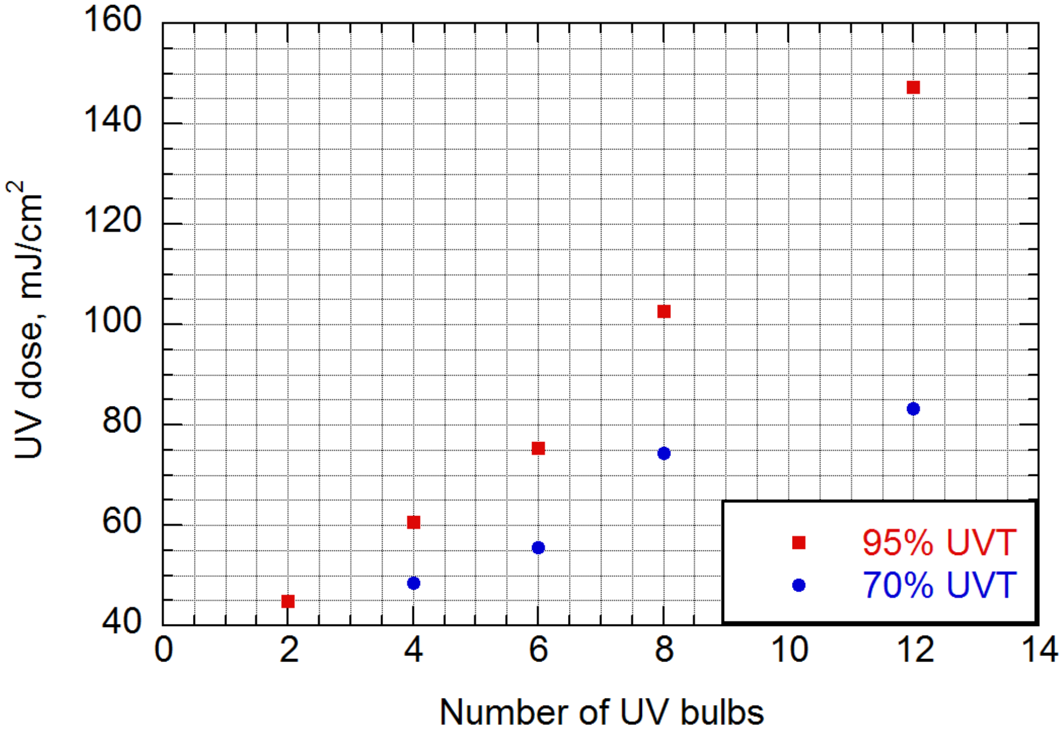
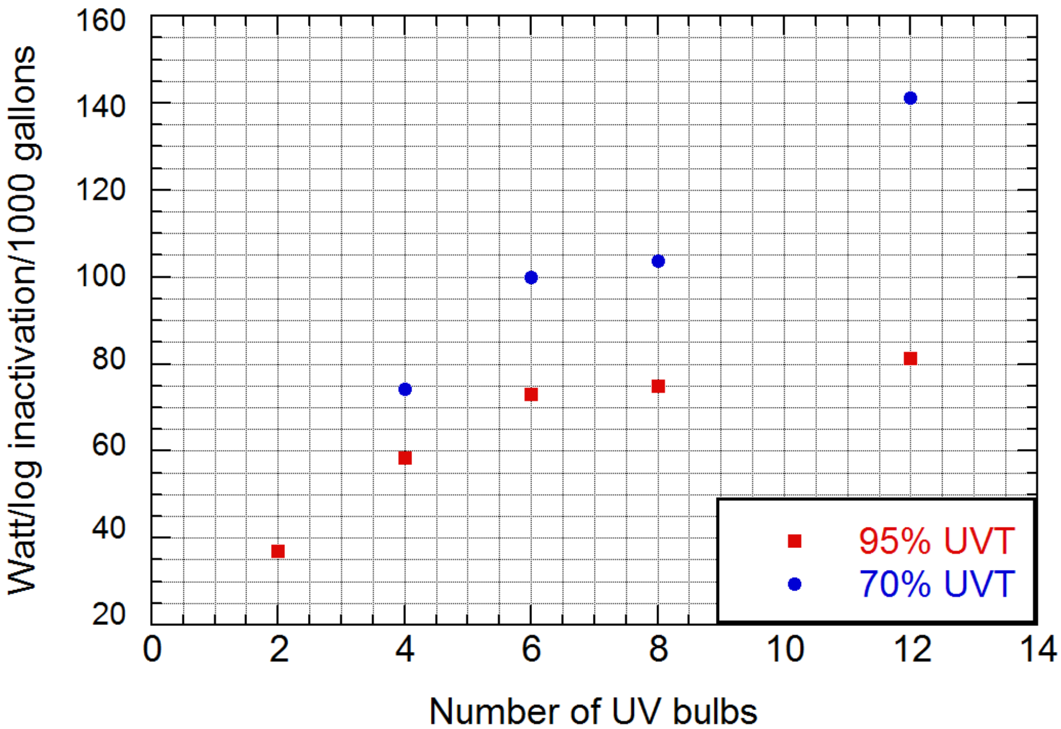


Figure 6-3: Energy Use per Log Inactivation



CHAPTER 7:
Degradation of Emergent Contaminants with Advanced Oxidation Processes

7.1 Background

Using advanced oxidation, a treatment of waste water with combination of UV light and oxidizing agent such as ozone or hydrogen peroxide, to remove emerging contaminants is well studied (Huber et al., 2003). Emergent contaminants are chemical and biological compounds, such as human hormones, pharmaceuticals, pesticides and personal care products, produced since the 1950s that are now appearing in the water supply and pose risks to environmental and human health. However, studies involving both the use of real wastewater streams and the generation of a comprehensive list of degraded chemicals in the water are rare (Young & Parry, 2013). Therefore, and to quantify, in situ, the vortex reactor's performance in the degradation of a host of chemicals and pharmaceutical products, this study's researchers collaborated with Professor Thomas Young (Department of Civil and Environmental Engineering, UC Davis) to use their novel high resolution mass spectrometry method that relies on mass accuracy and tandem mass spectrometry to determine the likely molecular formulas and structures of the chemicals found in the treated wastewater.

7.2 Advanced Oxidation Study

The UV reactor was placed in line with the secondary effluent from at the UCD Wastewater Treatment Plant's sand filters and was tested at a constant flow rate of 50 gallons per minute. A single lamp condition was tested, 12 UV lamps, and the concentration of hydrogen peroxide entering the system varied. The study used influent hydrogen peroxide concentrations of 15 mg/L and 200 mg/L. Two liters of sample was collected from the influent of the disinfection system and one liter for each hydrogen peroxide condition to allow for three analyses at each concentration, also known as analysis in triplicate.

Samples were prepped and analyzed at the University of California at Davis by Professor Young's research group. Samples were first filtered through a 1.0 μm filter (GF/B) and concentrated using a Supel-Select HLB (Sigma-Aldrich, 6cc/200mg) cartridge according to methods described by Young and Parry (2013). Samples were then analyzed with an Agilent 1200 HPLC combined with a 6530 quadrupole time-of-flight mass spectrometer (QTOF), also in accordance with methods described by Young and Parry (2013), to determine molecular features of chemical constituents in the water. Molecular features include the identification of "groups of isotopes, charge states, adducts, and multimers postulated to arise from individual compounds (Young & Parry, 2013)." Comparison of these molecular features and the change in abundance of these features in the untreated and treated samples was used to determine transformed chemical contaminants.

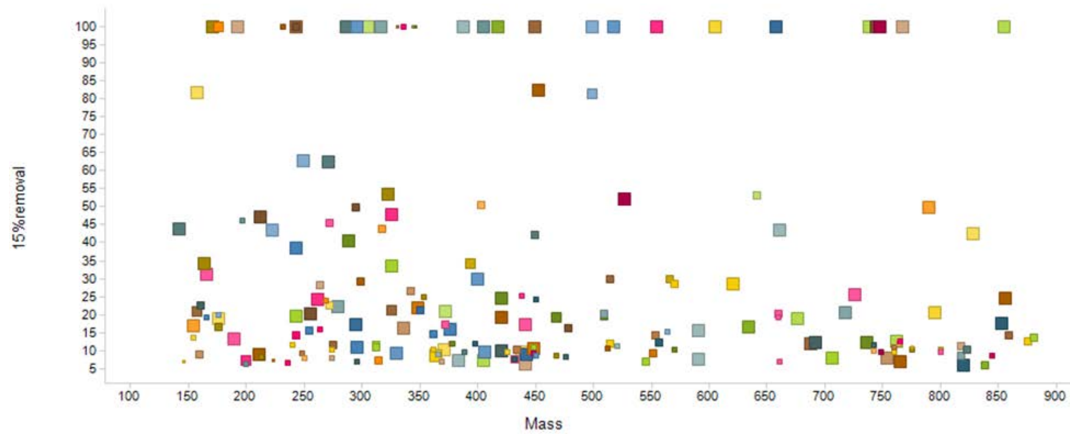
Table 7-1, adapted from Young and Parry (2013), is a summary of change in molecular features based on peroxide dose. Molecular features in this context include the identification of "groups of isotopes, charge states, adducts, and multimers postulated to arise from individual compounds" (Young and Parry, 2013). When chemicals are broken down their degradation products contain different molecular features, thus this study assessed the total change, increase and decrease, in each features to determine UV effectiveness. Combining different species some of which produced features that increased with degradation while others that were decreased, a total of 1,638 (1,231+407) features were found in the 200 mg/L samples and 1,562 (974+588) features were found in the 15 mg/L samples. The features in these samples that did not significantly change were then filtered out to find chemicals sensitive to this treatment method. The "filtered"analysis was performed on the filtrate, which contains the degraded chemicals. Thus, a low number of filtered molecular species in the filtrate indicates a greater amount of chemicals that were unchanged and collected on the filter. A total of 374 (161+213) filtered features were found in the 15 mg/L samples and 953 (687+248) features were found in the 200 mg/L samples. The results were then assessed for features that were common between these two treatments. A total of 248 (128+120) common features were found in both the 200 mg/L samples and the 15 mg/L samples. Results for each combination are presented as total/filtered/common and not surprisingly, more molecular species were removed at the higher peroxide concentration.

Table 7-1: Change in Molecular Features (Adapted from Young and Parry, 2013)

Peroxide dose	Molecular Features (total/filtered/common)	
	Decreased abundance	Increased abundance
15 mg/L	974/161/128	588/213/120
200 mg/L	1231/687/128	407/248/120

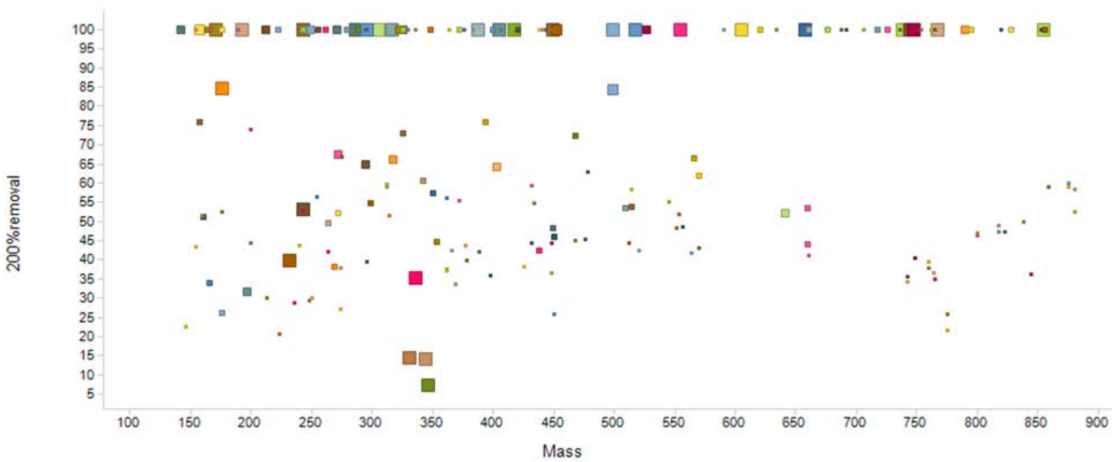
Shown in Figures 7-1 and 7-2 is the percent removal of each molecular feature plotted with respect to its molecular mass. Sizes of symbols in each figure indicate how much of that feature was removed with the alternate treatment method. Thus, the large symbols, seen more often in Figure 7-2, represent features with a high percentage of removal with hydrogen peroxide concentration of 200 mg/L.

Figure 7-1: Percent Decrease in Molecular Features Using 15 mg/L Hydrogen Peroxide



Source: (Young & Parry, 2013)

Figure 7-2: Percent Decrease in Molecular Features Using 200 mg/L Hydrogen Peroxide



Source: (Young & Parry, 2013)

Since the molecular mass of each feature can be determined, this information can be used to help identify what chemical type or name of each chemical feature. By evaluating the types of chemicals likely to degrade using this advanced oxidation indicates, one can determine what waste streams the technique is best suited for and what level of protection the advanced oxidation provides. The chemicals listed in Table 7-2, also adapted from Young and Parry (2013), were identified based on comparison of measured molecular mass and a database of wastewater contaminants, as well as commercial databases for forensics/toxicology and pesticides. Since a conclusive identification of chemical species should involve more than just comparison of molecular mass, only molecular masses which matched greater than 70 percent with the databases were accepted. Table 7-2 is a list of only compounds that were significantly removed at both 15 mg/L and 200 mg/L peroxide doses.

Table 7-2: List of Chemical Species That Significantly Degraded (From Young and Parry, 2013)

Amifloverine	Guaiazulene	Narcein
Androsterone	Dichlofenthion	Paroxetine
Benzhydrol	Dimethazan	Phensuximide
Bisphenol A	ESBP	Phenyldiallyl-acetamide
Chloramphenicol	Ethoheptazine	Prohydrojasmon
Fenocinol	Fenclorac	Psychotrine
Fluprednidene	Isoprednidene	Sulfamerazine
Fopirtoline	Meprobamate	Triamcinolone diacetate
Gemfibrozil	N-(2-hydroxyethyl)-10-Undecenamide	

CHAPTER 8: Validation for *Phytophthora ramorum* in Runoff Irrigation Water

Phytophthora ramorum, also known as Sudden Oak Disease (SOD), travels as zoonotic disease, such as the bubonic plague, with multiple intermediary hosts before reaching the dead-end host. Due to this mode of transportation, there are instances of pathogen moving from ornamental nurseries to the natural environment due to uncontrolled contamination (Ghimire et al., 2011). Nevertheless, few nurseries currently treat their recycled irrigation water (Banihashemi et al., 2010). Instead, nurseries use prophylactic fungicides to control the spread of fungal pathogens, which increases costs and promotes the growth of fungicide resistant fungi. In addition, theses fungal pathogens may be suppressed when under the presence of fungicides and proliferate when the fungicide is discontinued (Hong et al., 2003). For these reasons various techniques, including the use of chlorine, ozone and UV light, have been used to mitigate the spread of the pathogen, but each technique has its drawbacks.

It can be very costly for most small systems to treat recycled irrigation effluent. The most common treatment method used is liquid chlorine injection. This technique requires consistent addition, monitoring of chlorine concentrations, assessment of the system's water quality and on-site storage (Banihashemi et al., 2010). The chlorine dose needed is dependent on water quality because the high nitrogen and organic content in the dissolved and suspended matter incorporated in irrigation runoff increases the chlorine demand on the system. Ozone has similar limitations to using a liquid chlorine injection, but it can be generated on demand. However, ozone is not generally used due to high capital costs (Banihashemi et al., 2010; Hong et al., 2003).

Treatment using ultraviolet light has an advantage over chlorine and ozone because of the ease of maintenance and installation. However, the poor transmittance and turbidity of the run-off from dissolved and suspended matter in irrigation runoff also increases the required UV dose to inactivate *Pythium* and *Phytophthora* (of which *P. ramorum* is a sub-group) by two to four times (Banihashemi et al., 2010). The UV dose can be increased by decreasing the flow through the reactor, but a low flow can result in laminar flow which is poor for disinfection. Once flow becomes laminar, the UV dose is not equally distributed over each volume element in the reactor and active pathogens can leave the reactor (Crittenden, 2003).

The focus of this research is to minimize these problems in a novel reactor design and assess the UV reactors ability to inactivate *P. ramorum* in recycled irrigation water.

8.1 Testing at NORS-DUC

Testing of the UV reactor's performance with disinfection irrigation water took place at the National Ornamental Research Site at Dominican University California (NORS-DUC), San Rafael, California in October 2013. Laboratories at the research site both propagated the pathogen and processed samples from the experiment, because *P. ramorum* is a controlled pathogen in California.

For the experiment, irrigation water from the research site was collected and stored for seven days prior to the experiment to have enough volume to run the reactor at a flow of 35 gpm. The UV reactor was placed in line with the effluent from the collection basin and was tested at a constant flow rate of 35 gallons per minute and three lamp conditions on October 25, 2013. These lamp conditions include: 4, 8 and 12 lamps. One liter of sample was collected from the influent of the disinfection system and one liter for each lamp condition to test samples for bacteria and fungal counts. The transmittance of the water was 76.4 percent UVT.

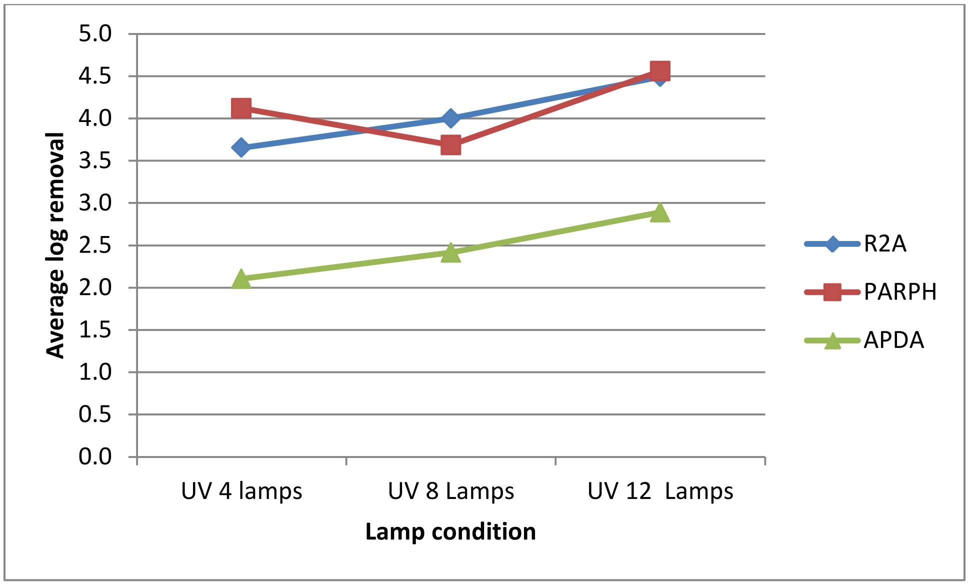
Bacterial counts were Reasoner's 2A media, Acidified potato dextrose agar (ADPA) media, and PARPH media. One milliliter of each sample was plated in triplicate on each media type and cultured using standard methods. Reasoner's 2A media is a minimal media which incubates at a low temperature, approximately 25°C, with a long incubation time, >48 hours (Van der Linde, Lim, Rondeel, Antonissen, & de Jong, 1999). R2A media is designed to culture bacteria found in treated or potable water sources, water sources with low concentrations of endogenous bacterial populations (Reasoner & Geldreich, 1985). ADPA is a media commonly used to culture fungal populations, but will cultivate some bacterial populations. Acidification helps to minimize the amount of bacteria that will grow on the media (Mislivec & Bruce, 1976). PARPH media is named after its components of pimaricin, ampicillin, rifamycin, PCNB, and hymexazol. It is a selective media designed to grow water molds, specifically Oomycetes, and is the typical media used to grow *P. ramorum* (Ferguson & Jeffers, 1999).

Table 8-1 and Figure 8-1 are summaries of the log reduction of bacterial counts from each UV bulb treatment and using each bacterial culturing method. Reduction in bacterial counts is measured in "log reduction," the number of bacterial cells removed on a log scale. For example, a 4-log reduction is a 10,000-fold decrease in microorganisms. Greater than 3.7 log removal was seen in the reactor for all lamp conditions for both the R2A media and PARPH media. Low bacterial counts were seen on the APDA media, because the acidification of the media suppresses bacterial growth.

Table 8-1: Summary of Bacterial Reduction in Irrigation Water Effluent October 25, 2013

	R2A		PARPH		APDA	
	Concentration, CFU/ml	**Log Reduction**	**Concentration, CFU/ml**	**Log Reduction**	**Concentration, CFU/ml**	**Log Reduction**
Influent	279,000		48,330		2,330	
UV 4 lamps	62	3.7	4	4.1	18	2.1
UV 8 Lamps	28	4.0	10	3.7	9	2.4
UV 12 Lamps	9	4.5	1	4.6	3	2.9

Figure 8-1: Average Log Removal of Bacterial Populations



Fungal counts were evaluated using APDA media and PARPH media. One milliliter of each sample collected from each lamp condition was plated in triplicate on each media type and cultured using standard methods. A problem occurred with spiking the system with *P. ramorum* and no counts appeared on the PARPH media. Fungal counts from the APDA media and each UV treatment are listed in Table 8-2. Disinfection removes about 92.4 percent, 96.3 percent, and 98.8 percent of fungal counts using 4, 8, and 12 UV lamps, respectively.

Table 8-2: Summary of Fungal Reduction in Irrigation Water Effluent October 25, 2013

	Concentration, CFU/ml	Log Reduction
Influent	243	
UV 4 lamps	18.3	1.1
UV 8 Lamps	9.0	1.4
UV 12 Lamps	3.0	1.9

Log reduction in total bacterial counts was also used to roughly estimate the UV dose applied to the system. This can be accomplished by comparing published data available for the dose response curve for wild type *E. coli* and total coliform and UV light and assuming a similarity of those species with species found in this wastewater stream. Sommer et al. (1998) established that it requires around 32.4 mJ/cm^2 for 4-log removal and 46 mJ/cm^2 for 5-log removal of wild type *E. coli*. Similarly, Chang et al. (1985) determined that it requires around 35 mJ/cm^2 for 4-log removal and 50 mJ/cm^2 for 5-log removal of total coliforms. Thus, based on log removal seen on the R2A and PARPH media plates, the reactor was operating at around 30 to 40 mJ/cm^2. APDA media plates were omitted, because the acidification of the media suppresses the growth of bacteria.

The UV dose standardizes UV reactor performance between different reactors to ensure a minimum level of disinfection. Similarly, higher UV doses are required depending on the pretreatment of the water and the intended use. For irrigation, pretreatment of the runoff would usually involve either media filtration or membrane filtration. For these types of pretreatment, Title 22 requires respective UV doses of at least 80 or 100 mJ/cm^2 (NWRI, 2012). Therefore, the number of UV reactors in series needed to treat this and similar irrigation water effluent streams can be determined using Title 22 requirements, and the predicted operating UV dose of the reactor (Table 8-3) (NWRI, 2012).

Table 8-3: UV Reactors in Series Needed to Meet Water Reuse Standards

Filtration Type	Title 22 UV Dose Requirements	UV Reactors in Series
Media Filtration (granular, cloth, synthetic)	100 mJ/cm^2	3
Membrane Filtration	80 mJ/cm^2	2 to 3

CHAPTER 9: Conclusions

9.1 Reactor Development and Demonstration

At the start of this project, the only item that was in existence was a vertical cylinder, made of Teflon, a material that does not allow for the transmission of UV light, and a basic method for generating a longitudinal vortex inside it. Funding from this grant enabled this basic concept to evolve into a novel system for water disinfection using UV light. The new system was subjected to rigorous testing at a number of operational facilities, specifically the wastewater treatment plants at UC Davis, the City of Winters, and the testing facilities at the National Ornamental Research Site in San Rafael, California. The outcome from all of these tests demonstrated that the new system inactivates harmful pathogens found in these wastewater streams to the level required by regulatory agencies. Further developments were introduced to allow for an oxidizing agent to be introduced into the water that is being treated in order to achieve an Advanced Oxidation Process (AOP). This process has been shown in previous studies to be necessary for breaking down emergent contaminants (such as pharmaceuticals and personal care products) that are becoming of increasing concern to the public and regulatory bodies. Tests conducted at the UC Davis wastewater treatment plant with the new reactor using hydrogen peroxide as the oxidizing agent on water that was dosed with a mixture of such contaminants demonstrated the ease with which the reactor can be adapted to accommodate an advanced oxidation process, and the efficacy of the new system in dealing with these contaminants.

Installing the reactor at operational water-treatment plants allowed for it to be demonstrated to professionals from the water quality communities. Among the specialists who viewed the reactor in operation were scientists from several California government agencies, private consultants, owners of horticulture and aquaculture businesses and researchers from such diverse fields as veterinary medicine and diseases of ornamental plants.

Tangible outcomes of the project included the application that was filed by the Regents of the University of California for a patent to protect the invention, a grant from the University of California Office of the President (UCOP) to commercialize the vortex reactor, an application to the Water Environment Research Foundation (WERF) to fund research on the use of the vortex reactor to breakdown Pyrethroids (toxic organic compounds that are present in the majority of commercial domestic insecticides), an application to the National Institutes of Health (NIH) under their Superfund Hazardous Substance Research and Training Program to further develop and validate the reactor's ability to breakdown emergent contaminants by using an Advanced Oxidation Process. Proposals are presently under consideration by two major utility companies aimed at installing the vortex reactor at two disadvantaged small communities in California that suffer from water shortages, but due to financial and technical constraints, do not as yet reuse the effluent from their water treatment plants as these do not meet the necessary regulatory standards. One of these proposals also entails extending the reactor's utility by having it energized by solar power. Finally, discussions are underway with a major manufacturer of UV water treatment system with view to licensing the vortex reactor.

9.2 Meeting the Title 22 requirements

The main conclusions of the tests carried out at the UC Davis Waste Water Treatment Plant and at the City of Winters plant were:

- The vortex reactor meets the requirements of Title 22 of the California Code of Regulations governing the reuse of treated water indoors and outdoors for waste streams similar to UCD secondary effluent.
- The reactor meets the Title 22 outdoor and outdoor requirements for waste streams similar to the City of Winters' secondary effluent. Additional filtering would be needed to meet turbidity and scaling requirements if the reactor is to be deployed on long-term basis.
- The robustness, energy efficiency and utility of the vortex reactor have been clearly demonstrated in operational settings.

Further studies should address the following needs:

- A long term biofilm growth study
- Quantitative analysis of change in UV-dose with respect to increasing turbidity
- UV-dose determination at higher flow rates
- The energy savings associated with this technology compared to traditional treatment technologies and methods.

9.3 Performance for emergent contaminants

Tests carried out at the UC Davis Waste Water Treatment Plant employing an Advanced Oxidation Process and using secondary effluent that was dosed by a mixture of pharmaceutical and personal care products support the following conclusions:

- Advanced oxidation using this reactor significantly degrades emergent contaminants in the UCD secondary effluent.
- Emergent contaminant degradation can be found using a non-targeted approach. This approach minimizes the problems of missing newly introduced chemicals, chemicals that are not the focus of research and degradation products.

Further studies should address these needs:

- Direct quantification of removal of specific emergent contaminants.
- Analysis at multiple flow rates and transmittances.
- Assessing the effectiveness of oxidizing agents other than hydrogen peroxide.

9.4 Inactivation of the quarantine pathogen *Phytophthora ramorum*

The tests performed at the National Ornamental research Site – Dominican University California support the following conclusions:

- Unfiltered irrigation run-off can be treated using the UV disinfection system embodied in the vortex reactor.
- Based on results obtained from unfiltered runoff water from their fields and which was dosed with the quarantine pathogen *Phytophthora ramorum*, two vortex reactors in series would be sufficient to treat water to meet water reuse standards.
- The reactor's suitability for deployment in this operational setting was demonstrated.

Further studies should address the following:

- Determination of the dose response curve for *Phytophthora ramorum*.
- Assessment of the conditions for when additional treatment (e.g. fungicide/pesticide breakdown and removal of color) may be needed.
- Water Quality Modeling for best operational parameters.

GLOSSARY

Term	Definition
ADPA	Acidified potato dextrose agar
ATCC	American Type Culture Collection
AOP	Advanced Oxidation Process
APHA	American Public Health Association
CFU	Colony Forming Unit
GF/B	Glass Fiber/Grade B – A filter made of boroscilicate glass fibers
MPN	Most Probable Number
MS2	Bacteriophage. An icosahedral, positive-sense single-stranded virus that infects the bacterium E-Coli. MS2 is a male-specific (F+) RNA coliphage virus that infects the bacterium *E. coli*. It is used to assess UV disinfection because it has a similar structure to the polio virus and requires a dose of approximately 20 mJ/cm^2 to remove one log of MS2.
ND	No Detect
NTU	Nephelometric Turbidity Units
NWRI	National Water Research Institute
NORS-DUC	National Ornamental Research Site – Dominican University California
PARPH	Growth media for Phytophthora isolation procedure
PFU	Polyurethane foam unit
QTOF	Quadrupole Time of Flight
UV	Ultra Violet
UVT	UV Transmittance
WWTP	Waste Water Treatment Plant

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APPENDIX A:
Theoretical Considerations

The vortex-like motions observed in the cylinder consists of a forced vortex at the central core with R radius and free vortex outside the core to the wall of the cylinder. The size of R in the real flow depends on the tangential velocity, viscosity, turbulence, etc. The model is called *Rankine's combined vortex*.

A.1. Velocity

Within the core, $r \le R$

Circulation is defined as the integral of the scalar product of the vector velocity, ν, times vector displacement, *l*, around a closed curve, *c*, at some instant, given as

$$\Gamma = \int_c v \cdot dl \qquad (1)$$

By Stroke's Theorem, vorticity integrated over a closed surface is equal to circulation around its periphery, therefore,

$$\Gamma = \int_c v \cdot dl = \int_S \zeta \cdot dS$$

$$\Gamma = \pi R^2 \zeta \qquad (2)$$

which is much easier to compute.

In case of forced vortex, vorticity is uniform everywhere, i.e.,

$$\zeta = 2\ \omega \qquad (3)$$

The vortex strength equivalent to this Γ is

$$\kappa = \Gamma / 2\pi = R^2 \zeta / 2 \qquad (4)$$

By re-arrange equation, it gives

$$\zeta = 2\kappa / R^2 \qquad (5)$$

Velocity as a function of this vortex strength, κ, is given by

$$\nu_\theta = \kappa r / R^2 = \frac{\Gamma}{2\pi r} = \omega r \qquad (6)$$

Therefore,

$$\omega = \kappa / R^2 b \qquad (7)$$

where $r \le R$ and ω is the angular velocity of the rotating core.

Outside the core, r>R

In case of free vortex, ζ=0 everywhere, except in the center, which does not exist in our case. So, the circulation, Γ, is always zero outside the core.

Velocity is given by

$$v_\theta = \frac{\kappa}{r} \qquad (8)$$

where $r>R$ and κ is the vortex strength.

The velocity at r = R become $v_\theta = \kappa/R$.

A.2. Pressure Distribution

Within the core, $r \leq R$

Pressure is continuous over radius, r. Inside the core the radial pressure gradient at a point is equal to the density times centripetal acceleration at the point, i.e.,

$$\frac{dp}{dr} = \rho \, \mathrm{r}\omega^2 \qquad (9)$$

Using equation (7), it becomes

$$\frac{dp}{dr} = \frac{\rho\, r\kappa^2}{\mathrm{R}^4} \qquad (10)$$

Integrate the equation gives

$$\mathrm{p}_1 = \mathrm{p}_0 + \frac{\rho\, r^2\kappa^2}{2\mathrm{R}^4} \qquad (11)$$

where p_0 is the pressure at the center and p_1 is the pressure inside the core.

Outside the core, r>R

Outside the core is irrotational flow, the Bernoulli equation applies. Equating conditions at r_∞, where $v_\theta = 0$, gives

$$\frac{p}{\rho} + \frac{v_\theta^2}{2} = \frac{p}{\rho} + \frac{\kappa^2}{2r^2} = \frac{p_\infty}{\rho} \qquad (12)$$

Therefore,

$$p_2 = p_\infty - \frac{\rho\kappa^2}{2r^2} \qquad (13)$$

Since the pressure is continuous at r = R, equating p_1 and p_2 gives

$$p_\infty - p_0 = \frac{\rho\kappa^2}{R^2} \qquad (14)$$

This shows the relationship between the vortex strength and pressure at center and at infinity.

At r = R, equation (14) becomes

$$p_R = p_\infty - \frac{\rho\kappa^2}{2R^2} \qquad (15)$$

A.3. Profile

Within the core, $r \le R$

As the pressure gradient in the vertical z direction is only governed by gravitational force, therefore,

$$\frac{\partial p}{\partial z} = -\rho g \qquad (16)$$

The pressure is everywhere constant at atmospheric pressure on the free surface, i.e., $dp = 0$. By total derivative,

$$dp = \frac{\partial p}{\partial r}dr + \frac{\partial p}{\partial z}dz = \rho\omega^2 r dr - \rho g dz \qquad (17)$$

Therefore, along the free surface

$$\frac{dz}{dr} = \frac{\omega^2 r}{g} \qquad (18)$$

Integrating this expression, the variation of the z-coordinates of the free surface with r is given as

$$z = \frac{\omega^2 r^2}{2g} + z_0 \qquad (19)$$

where z is the elevation above a reference z–datum, constant z_0 is the elevation at the vortex center above datum.

This equation shows that the free surface profile varies in an r^2 manner.

Outside the core, r>R

Apply the Bernoulli equation between point 1 and an arbitrary point, point 2, on the free surface at radial distances r_1 and r_2 from the core center respectively:

$$z_1 + \frac{p_1}{\rho g} + \frac{v_1^{\,2}}{2g} = z + \frac{p}{\rho g} + \frac{v^2}{2g} \tag{20}$$

where

z_1, z are the elevations above a z –datum,

p_1, p are the pressures and

v_1, v are the velocities at points 1 and 2 respectively.

As the pressure is constant at atmospheric pressure on the free surface, the equation is reduced to:

$$z_1 + \frac{v_1^{\,2}}{2g} = z + \frac{v^2}{2g}. \tag{21}$$

Therefore, the elevation of an arbitrary point on the free surface at a radial distance r from the center is given by:

$$z = z_1 + \frac{\Gamma^2}{8\pi^2 r_1^{\,2} g} - \frac{\Gamma^2}{8\pi^2 r^2 g}$$

$$z_1 + \frac{(\frac{\Gamma}{2\pi r_1})^2}{2g} = z + \frac{(\frac{\Gamma}{2\pi r})^2}{2g}$$
$$z_1 + \frac{\Gamma^2}{8\pi^2 r_1^{\,2} g} = z + \frac{\Gamma^2}{8\pi^2 r^2 g}$$

(22)

If point 1 is at a large distance from the vortex center, i.e., $r_1 \to \infty$, the fluid level can be considered to be undisturbed by the vortex flow. If the undisturbed level is denoted by z_∞, then because $\frac{1}{r_1^{\,2}} \to 0$ as $r \to \infty$, therefore,

$$z = z_{\infty} - \frac{\Gamma^2}{8\pi^2 r^2 g} \qquad (23)$$

where z is the elevation above a reference z–datum, constant z_0 is the elevation at the vortex center above datum. This can be described as that the drop of the free surface from the undisturbed level varies in a $\frac{1}{r^2}$ manner.

APPENDIX B: Laboratory Reports

Included in this Appendix are the front pages of a selection of reports from certified commercial laboratories where samples of effluents from the vortex reactor were tested.

The front pages from the following reports are included:

1. Report from the California Laboratory Services for testing for total coliforms. Water sample taken from the UCD WWTP.
2. Report from the laboratory at the UCD WWTP of tests performed in accordance with their own procedures that are in compliance with the requirements of their discharge permits.
3. Report from Professor Wuertz's laboratory including tests on viruses.
4. Report from ExcelChem Environmental Laboratories on tests performed at the City of Winters WWTP.
5. Report from BIOVIR Laboratories performed on MS2 dosed effluent from the UC Davis WWTP.

CALIFORNIA LABORATORY SERVICES

3249 Fitzgerald Road Rancho Cordova, CA 95742

August 08, 2011

CLS Work Order #: CUH0029
COC #:

Bassam Younis
UC Davis Civil and Environmental Engineering
One Shields Avenue
Davis, CA 95616

Project Name: Coliform Testing

Enclosed are the results of analyses for samples received by the laboratory on 08/01/11 12:50. Samples were analyzed pursuant to client request utilizing EPA or other ELAP approved methodologies. I certify that the results are in compliance both technically and for completeness.

Analytical results are attached to this letter. Please call if we can provide additional assistance.

Sincerely,

James Liang, Ph.D.
Laboratory Director

CA DOHS ELAP Accreditation/Registration number 1233

University of California – Davis
WWTP Environmental Laboratory (ELAP #2343)
One Shields Avenue
Davis, CA 95616

UC Davis – Water/Waste Services
One Shields Ave.
Davis, CA 95616

Project: BAY Project

Sampled: 10-Aug-2011 9:59 am
Received: 10-Aug-2011 10:02 am

Total and Fecal Coliform - MPN
Standard Methods 18th Edition – 9221 (B & E)

Analyte	Date Analyzed	Reporting Limit	Result	Final Results Read:
BAY Sample	10-Aug-2011 10:12 am	2 MPN	Total = < 2 MPN	12-Aug-2011 9:17 am

Note: All samples were collected, preserved and received in compliance with Standard Methods 18th Ed.

WWTP Environmental Laboratory
Mindy Boele – Lab Manager
(530) 754-5819

!

Analysis Report
Dr. Wuertz Laboratory

University of California, Davis
Department of Civil & Environmental Engineering
One Shields Avenue
Davis, CA 95616

!
!

August 11, 2011

ATTN: Bassam Younis

The analytical results for indicator bacteria and pathogens performed on two samples received on August 10, 2011 are summarized below.

Colilert or Enterolert was performed for following bacteria:

- Total coliform
- *E.coli*
- Fecal coliform
- *Enterococcus*

Samples were analyzed via qPCR for following markers:

- *Enterococcus*
- Universal *Bacteroidales*
- Human *Bacteroidales*
- Cow *Bacteroidales*
- Dog *Bacteroidales*
- *Campylobacter*
- *Salmonella*
- *Vibrio cholera*
- *Cryptosporidium*
- *Giardia*
- *Toxoplasma*
- Adenovirus C
- Adenovirus 40/41
- Norovirus GI
- Norovirus GII
- Rotavirus
- Enterovirus

The PureLinkTM viral RNA/DNA kit (Invitrogen) was used for extraction of the water samples. Please let me know if you have any questions regarding the results or the analysis. Thank you very much.

Regards,

Minji Kim

43-4449

09 July 2013

Bassam Younis

UC Davis Office of Environmental Health & Safety

One Shields Ave

Davis, CA 95616

RE: Winters UV

Work order number:1307051

Enclosed are the results of analyses for samples received by the laboratory on 07/02/13 13:35. All Quality Control results are within acceptable limits except where noted as a case narrative. If you have any questions concerning this report, please feel free to contact the laboratory.

Sincerely,

BioVir Laboratories, Inc

NELAC #05234CA
EPA ID# 01401, CA-ELAP #179

685 Stone Road, Unit 6 • Benicia, CA 94510 • (707) 747-5906 • 1-800-GIARDIA • FAX (707) 747-1751 • WEB: www.biovir.com

REPORT NO.:	131234
PAGE NO.:	1 of 3
CLIENT:	University of California, Davis
ADDRESS	Department of Civil and Environmental Engineering Main Office, Room 2001 Davis, CA 95616
CLIENT NO	UCD002 **CLIENT PO:** 3PR03G0076

ASSAY RESULTS:

Test: **Bacteriophage Male-Specific** **Method:** **Adams 1959**

BioVir #	Sample ID	Site	Analyte	Result	Units
131234-001	In - 100%		Bacteriophage, Male Specific	8.9e7	pfu/mL

Collector: Laura Mahoney CollectDate 8/29/2013 CollectTime: 8:40:00 AM
ReceiveDate 8/29/2013 10:55:00 AM Matrix: Water, not otherwise specified Temp 17.7
Volume: 100 mL Analysis Start Date: 8/29/13 Analysis Start Time: 1507
Analyst: JTruscott Analysis End: 9/1/2013

Comment

BioVir #	Sample ID	Site	Analyte	Result	Units
131234-002	4 - 100%		Bacteriophage, Male Specific	2.3e5	pfu/mL

Collector: Laura Mahoney CollectDate 8/29/2013 CollectTime: 8:48:00 AM
ReceiveDate 8/29/2013 10:55:00 AM Matrix: Water, not otherwise specified Temp 17.7
Volume: 100 mL Analysis Start Date: 8/29/13 Analysis Start Time: 1507
Analyst: JTruscott Analysis End: 9/1/2013

Comment

BioVir #	Sample ID	Site	Analyte	Result	Units
131234-003	6 - 100%		Bacteriophage, Male Specific	7.1e4	pfu/mL

Collector: Laura Mahoney CollectDate 8/29/2013 CollectTime: 8:46:00 AM
ReceiveDate 8/29/2013 10:55:00 AM Matrix: Water, not otherwise specified Temp 17.7
Volume: 100 mL Analysis Start Date: 8/29/13 Analysis Start Time: 1507
Analyst: JTruscott Analysis End: 9/1/2013

Comment

BioVir #	Sample ID	Site	Analyte	Result	Units
131234-004	8 - 100%		Bacteriophage, Male Specific	8.3e3	pfu/mL

Collector: Laura Mahoney CollectDate 8/29/2013 CollectTime: 8:44:00 AM
ReceiveDate 8/29/2013 10:55:00 AM Matrix: Water, not otherwise specified Temp 17.7
Volume: 100 mL Analysis Start Date: 8/29/13 Analysis Start Time: 1507
Analyst: JTruscott Analysis End: 9/1/2013

Comment